

Giant pulse emission from PSR B0950+08

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ABSTRACT

We present here the detection of giant-pulse emission from PSR B0950+08, a normal-period pulsar. The observations, made at 103 MHz and lasting for about ten months, have shown on a number of days the frequency of occurrence of giant pulses to be the highest among the known pulsars. The flux-density level of successive giant pulses fluctuates rapidly and their occurrence rates within a day's observations as well as between neighboring days show large variations. While on some days PSR B0950+08 shows a large number of giant pulses, there are other days when it shows only “quasi-nulls” with no detectable emission in the power spectrum or in the folded pulse data. The cumulative intensity distribution of these giant pulses appears to follow a power law, with index -2.2 . After eliminating instrumental, ionospheric, interplanetary and interstellar diffractive and refractive scintillation effects as the cause, it appears that these intensity variations are intrinsic to the pulsar. We suggest that the giant pulse emission and nulling may be opposite manifestations of the same physical process, in the former case an enhanced number of charges partaking in the coherent radiation process giving rise to an extremely high intensity while in the latter case the coherence could be minimal.

Subject headings: stars: pulsars: general — stars: pulsars: individual: PSR B0950+08
— radio continuum: stars

1. Introduction

At radio wavelengths, pulsars show pulse to pulse intensity variations which lie typically within an order of magnitude of the average pulse strength. However, in about half a dozen pulsars, the pulse intensity is seen to sometimes exceed the mean pulse strength by much more than that. These are called giant pulses. With the exception of the Crab pulsar (Lundgren et al. 1995), PSR B1937+21 (Cognard et al. 1996) and a handful of other cases (see Knight 2006), pulses much stronger than 10 times the mean have not generally been seen, and pulsars with giant pulses seem to be rather uncommon (Johnston & Romani 2002). Triggered by a chance observation of a large

number of giant pulses on August 8, 1997 (Vats et al. 1997; Singal, Vats & Deshpande 2000) from the extremely variable pulsar PSR B0950+08 (Pilkington et al. 1968; Cole, Hess & Page 1970), we undertook a long-term monitoring program of this object at 103 MHz by observing it daily for half an hour. The aim was to confirm and study the nature of these giant pulses from their cumulative intensity distribution and from the fluctuations in their occurrence rate as well as long-term variations, if any, in their daily mean. Such statistical knowledge is still lacking, not merely because only a few pulsars are known to exhibit giant pulse phenomenon but also because to monitor such sources on a regular basis to get their temporal statistics it may require a fairly large amount of precious telescope time, spread over many months or longer, which may be difficult to get allotted. We found some curious results for PSR B0950+08 in its giant pulse emission.

In recent literature (Johnston et al. 2001; Cairns 2004) a distinction is made between giant pulses and giant micropulses, the latter being short-duration intense events that may have phase-resolved flux densities more than 10 times the average flux density but have pulse-integrated flux density less than 10 times the average, and are thus not called giant pulses. The Vela pulsar (Johnston et al. 2001), B1706-44 (Johnston & Romani 2002), J0437-4715 (Jenet et al. 1998) and even B0950+08 (Cairns, Johnston & Das 2004) have been classified as giant micropulse cases. But here we show that B0950+08 emits giant pulses as their pulse-integrated flux does exceed the average pulse strength by 10 times or even much more.

2. Observations

Our observations were made with the Rajkot radio telescope, situated at a location (longitude 70.7° E, latitude 22.3° N) in the western part of India (Vats et al. 1999). The telescope is a transit instrument, consisting of 1024 dipoles spread over a 5000 square meter area, with a maximum antenna spacing of 64λ in the north-south and 7.5λ in the east-west. The telescope, designed in the 1970s primarily for the interplanetary scintillation (IPS) studies, operates at a center frequency of 103 MHz, with a bandwidth of 1.6 MHz, and has only a single polarization. The wide east-west beam ($\sim 8^\circ$) of the telescope allows an object near the meridian to be studied for about half an hour, the north-south pointing is done using the phased array technique. The sampling time interval selected for IPS observations is 48 ms, with a receiver time constant of 100 ms. Our initial observations (on August 8, 1997) came from regular IPS monitoring of 3C237 which follows PSR B0950+08 in right ascension by about 15 minutes. On these records we noted that on some days there were a large number of very intense pulses from PSR B0950+08. We decided to monitor this pulsar more regularly, throughout the year. Though an occurrence of some very intense pulses from PSR B0950+08, observed at 103 MHz, were reported on an earlier occasion (Deshpande et al. 1994), the nature of these as regular giant pulses was not recognized at that time. For the sake of consistency with our initial observations, we decided to continue with the same observational setup. Since the dispersion measure for PSR B0950+08 is small ($DM \sim 3 \text{ pc cm}^{-3}$) the expected smearing ($\sim 36 \text{ ms}$) across the band is not too detrimental for the observational setup, more so

as our aim was to study the total pulse intensity. We obtained a total of 141 days of successful observations during the period July 1997-May 1998. Useful observations could not be made on other days due to instrumental problems, presence of heavy radio interference or due to a simple shortage of manpower. In these 141 days, with daily 32 minute observing periods, data for more than a million pulses ($P = 253$ ms) have thus been recorded, yielding a mean pulse intensity of ~ 3 Jy. While most individual pulses were too weak to be detected (signal to noise $\lesssim 0.2$), single giant pulses may greatly exceed the noise level. We have chosen 10 times the mean (~ 30 Jy) as the threshold pulse intensity for a pulse to be called giant. This definition is consistent with the usage in the recent literature (Karuppusamy, Stappers, & van Straten 2010) and safeguards against the inclusion of any significant number of spurious giant pulses. To minimize the effect of radio interference, individual giant pulses were identified by their phase; further we rejected all records with a certain amount of discernible radio interference. Daily calibrations were done before and/or after the observations using 3C196 and 3C273.

3. Results

Some details of the giant-pulses statistics are available in the literature, but for only a couple of pulsars. For the Crab pulsar about 2.5 percent of all pulses were observed to have pulse intensity more than 20 times the average value (Lundgren et al. 1995), while Cognard et al. (1996) found that in the millisecond pulsar PSR B1937+21 about one pulse per ten thousand exceeded 20 times the mean “pulse-on” flux density. Among our approximately one million pulses, the corresponding number (i.e., with pulse strength 20 times the mean pulse-on flux density) was found to be $\sim 1\%$ of the total, while about one in ten thousand was as large as 100 times the mean pulse level, with some individual pulses exceeding the mean by a factor of 300. This makes PSR B0950+08 one of the most active pulsars known, though we have to keep in mind that the differences in the observing conditions and the way the threshold pulse intensity values are chosen or defined could influence such comparisons. One additional feature of our data is that the distribution of giant pulses is not uniform. There is a large fluctuation in the giant pulse occurrence rate from one day to other. Almost all ($\gtrsim 99\%$) of the total giant pulses seen by us occurred during 35 or so “active” days out of our 141 days of observations, i.e., about one fourth fraction. Even out of these there were about a dozen particularly active days where more than five percent of the total pulses observed were giants. On these particular days PSR B0950+08 exhibited the highest rate of occurrence of giant pulses seen from any pulsar. On the other hand $\sim 20\%$ of the days (27 out of 141) showed only “quasi-nulls” when no detectable emission was seen either in the folded pulse data or in the power spectrum. No giant pulse was generally seen on these silent days and the mean flux density of the pulse on the day (for 32 minutes of observations) was below ~ 0.3 Jy, implying that generally the pulse intensities on such days are at least an order of magnitude below the normal average pulse intensity of 3 Jy. Since the fraction of giant pulses and quasi-nulls seems to vary so drastically from one day of observation to the other, the conflicting nulling fraction reported by Smith (1973) and Hesse and Wielebinski (1974) on one hand and by Ritchings (1976) on the other, could simply

be due to their different epochs of observations.

Figure 1 shows a sample of four days of consecutive observations. Figure 2 shows the corresponding power spectra. We notice that the giant pulse activity changes very drastically from one day of observing to the other. In order to quantitatively compare the variation in giant pulse activity from one day to the other, we made use of the fact that there is almost a one to one correspondence between the rate and strength of giant pulses seen on each day and the daily average pulse intensity value. This is seen in Figure 3 which shows a plot of the daily average pulse intensity values obtained from the average folded pulse profiles, generated using the precomputed pulse period for our telescope location and time of the day’s observations. From Figure 3 we see that the daily average between day numbers 54 and 59 mimics the change in giant pulse activity between 23/02/98 and 28/02/98 seen in Figures 1 and 2. The plot shows that starting from a quiet phase, when there is hardly any detectable pulse emission, there is a build up time of 1-3 days for the pulsar to change into an active phase, with large average pulse intensity, which is followed by a similar time interval of “decay” to the quiet level. And such behavior seems to repeat again and again. Whether there is any quasi-periodicity in this cycle, on say, a 3–4 days period, needs to be checked. But for that one has to first make sure of the time scales of variations which could actually be smaller as our interpretation is based on the observations taken through a half-an-hour time window every 24 hours of sidereal time. Both the very large percentage of giant pulses on some days and the frequent switching between days of extreme quietness and of giant-pulse activity makes PSR B0950+08 perhaps the most violently variable among the known pulsars.

The process that gives rise to *individual* giant pulses seems to be quite erratic. Even on days of extreme giant pulse activity, when more than five percent of all pulses are giants, the giant pulses seemed to occur quite randomly. It is only one third of the time that a couple of giant pulses followed each other in quick succession. Most of the time, giant pulses appeared in isolation with pulses on either side being more than an order of magnitude lower in intensity, and often falling below the noise level. There were large quiet intervals, often extending to many pulse periods, when no giant pulse was seen. Such behavior was seen to repeat on many days.

In both the Crab pulsar and PSR B1937+21, the cumulative distributions of the giant pulse intensity, S , have been shown to follow a power law $N(> S) \propto S^\alpha$ (Argyle & Gower 1972; Lundgren et al. 1995; Bhat, Tingay & Knight 2008; Cognard et al. 1996; Kinkhabwala & Thorsett 2000). For PSR B0950+08 we have examined the cumulative distribution of pulse intensity on the days of giant pulse activity. As an example we show in Figure 4 a plot of the normalized cumulative distribution of pulse intensities for PSR B0950+08 for three different days. Also shown are the power-law fits to the observed distributions, which yield the best-fit values for the index α to be in a tight range around -2.2 ± 0.2 . This value for α is quite similar to those found in the case of the Crab pulsar ($\alpha \simeq -2.3$; Lundgren et al. 1995) and PSR B1937+21 ($\alpha \simeq -1.8$; Cognard et al. 1996). In fact there may even be further resemblance between the giant pulse distributions in PSR B0950+08 and the Crab pulsar. In figure 4 we notice that the cumulative distribution at less than 30 times the average intensity falls below the fitted line on all three days, perhaps

indicating a departure from the power-law. If we ignore the lower pulse intensity points and make a fit only to the higher intensity (> 30 times the average) then the power law index is steeper, close to -2.7 ± 0.2 . This trend is quite similar to that seen in the case of the Crab pulsar, where the slope tapered off at intensities close to the giant pulse threshold level (Lundgren et al. 1995; Karuppusamy et al. 2010). Thus the process responsible for the giant pulse phenomena might be rather similar in such cases.

Cairns et al. (2004) have found B0950+08 to emit giant micropulses which according to them do not meet the criteria of being called giant pulses, as their pulse-integrated flux does not exceed 10 times the average pulse-integrated flux. We may point out that as discussed above, the giant pulse activity in B0950+08 seems to vary so much from day to day that it will not be surprising if observations lasting for only about half an hour on a single day (7072 pulses of Cairns et al. 2004), which is in fact very close to the time interval for our daily observations, does not show very large pulses. Our observations which represent the pulse-integrated flux analysis do show the individual pulse intensity to exceed the average value by more than a factor of 10 in $\sim 5\%$ of the total pulses on “active days”.

4. Discussion

The origin of these giant pulses can be traced to the pulsar itself. One can unambiguously rule out any instrumental effects like large gain fluctuations of the receiver system masquerading as giant pulses. The calibrated noise level in the records does not fluctuate by any appreciable amount from one day to the other (Fig. 1) irrespective of the level of the giant-pulse emission seen. Nor could these be any interference spikes as the periodicity of the pulsar is so clearly visible in the spectral plots in Figure 2. One can also rule out any ionospheric or interplanetary scintillation effects as the cause since our observations have been carried out both during day and night times, depending upon the time of transit of the source during different months over the year, and no systematic differences in the giant-pulse emission rates are found in the records.

The fluctuations in the pulse intensities on different time scales have also been explained by the diffractive and refractive scintillations of the interstellar medium; especially, the long term changes in flux density on time scales of days or longer have been explained in terms of RISS (refractive interstellar scintillation; Rickett, Coles & Bourgois 1984). The time scales for the build up of individual giant pulses, as observed by us, are too fast for the scintillation effects to explain them. As we have already mentioned, in the case of giant pulses, the pulse intensity is often larger than that of the neighboring pulses by much more than an order of magnitude. These enhancements in intensity sometimes last over a few consecutive pulses, but more often than not these enhancements may have much shorter durations (\lesssim a pulse period) and with the consecutive giant pulses quite often separated by many pulse periods. Thus the rise/fall time for the giant pulse emission in our observations is at most up to a few pulse periods, which is many orders of magnitude smaller than the time scales of scintillation. The diffractive time scales for PSR B0950+08 at 103 MHz are

estimated to be about 10 minutes, while the time scale of RISS is expected to be around 47 days, calculated from the values given for 74 MHz by Gupta, Rickett & Coles (1993). Thus these extreme intensity enhancements of individual giant pulses cannot be explained by diffractive or refractive scintillation and it can therefore be construed that the giant pulses seen by us are intrinsic to the pulsar.

Even though some presence of interstellar scintillation in our data cannot be ruled out, none of the variations that we have reported here can be wholly explained by the scintillation. We may point out that a slow intensity variation visible in Figure 1, peaking near the middle of each day’s plot, is merely the east-west primary beam pattern of our telescope, which is a transit system, and that corrections for this primary beam pattern were made before any further analysis. The observed variability time scale of 3–4 days in Figure 3 is too slow for diffractive scintillation but too fast for refractive. The change in the daily average by a factor of $\gtrsim 70$ (from about $\lesssim 0.3$ to $\gtrsim 20$ Jy) just in a day’s time, does not fit with the expected refractive time scales. These day to day variations in the average intensity, and the giant pulse rate, appear to be among the most extreme for pulsars. For example, in the case of the Crab pulsar, Lundgren et al. (1995) have seen day to day intensity variability to be $\approx 50\%$ of the average flux density, along with a factor of two change in the rate of giant pulses observed, and these they have attributed to RISS, which has a characteristic time scale of 2-5 days for their observing parameters. On the other hand for PSR B0950+08 the variations in the daily-average intensity are about an order of magnitude as compared to the predicted modulation index of ≈ 0.22 (implying expected rms fluctuations of about 22% in intensity) at 103 MHz (see Gupta et al. 1993). The fluctuations in the giant pulse rate are equally drastic with some days showing hardly any unambiguous giant pulses, while the very next day may show as many as 300-400 giant pulses during our daily half an hour of observing. These extreme variations are much beyond the standard scintillation predictions.

The use of a daily mean instead of the global mean for defining a threshold level for giant pulses may appear preferable. However, a problem in the use of daily mean is that whenever there will be a large fraction of genuine giant pulses, the daily mean value will also accordingly go up (even in the absence of scintillation). In fact if we mask out the giant pulses (which are only a small fraction of the total number of pulses, at most 5 percent on very active days), then the daily mean drops substantially closer to the global mean. We may add here that even if we use a “pulse-on” daily mean, still we find a fairly large number of pulses in our data that exceed the mean by more than an order of magnitude, something rarely ever seen in other pulsars. For example on 28/02/98 (Fig. 1 and 3) the daily mean is about 25 Jy, and there are about 20 pulses with a flux density higher than 250 Jy, that is ten times that day’s “pulse-on” mean. Even on 23/02/98 the daily mean is about 7 Jy, and there are again about 50 pulses with flux density higher than 70 Jy on that day. Further, as we mentioned earlier, most of the giant pulses occur in isolation without another giant pulse in close proximity. Both these facts imply that it is not the overall level of the pulsar intensity that got boosted up by scintillation. In spite of it, if we were nonetheless to ascribe daily variations to some *extreme* interstellar scintillation effects, and to then assume that an

increase in the number of giant pulses observed above a threshold on some days is merely a result of an increase in the overall pulse intensity due to scintillation, it will still be very hard to explain the presence of large variations *within* this scintillation-enhanced intensity (by more than an order of a magnitude) in at most a few pulse periods (less than a second of time!). Such fluctuations have never been seen earlier in other pulsars (except of course in giant-pulse emitting pulsars), and are too fast to be due to scintillation. The daily variations that result from the fluctuation in the contribution of the giant pulse intensity too are then intrinsically arising from the pulsar, with the interstellar scintillation playing only a minor role, if any.

In order to make sure that in spite of the shortcomings, like the absence of full polarization, a large sampling rate of 48 ms and the pulse smearing (~ 36 ms) across the band due to dispersion, our Rajkot data are still meaningful, we observed this pulsar with the Westerbork Synthesis Radio Telescope (WSRT) using the Pulsar Machine (PuMa, Strom 2002) at 297 MHz. We also observed the pulsar with the Ooty Radio Telescope (ORT, Swarup et al. 1970) at 327 MHz for a number of sessions lasting a few hours each. In both WSRT and ORT observations (Singal, Manoharan & Strom 2002) a trend similar to as seen at Rajkot was noticed. It seems that both the frequency and the strength of the giant pulses may vary over a few hour time scale at these frequencies. There are stretches where pulses almost disappear (quasi-nulling!), to be followed within several hours by pulses as much as two orders of magnitude above the average pulse strength. These time scales appear to be too short for either the refractive or diffractive interstellar scintillation, and we see a similar pattern at frequencies which differ by a factor of three. Figure (5a) shows a record from the WSRT while figure (5b) shows one from the Rajkot Telescope (both records belong to different dates). A comparison of giant pulses in (5a) and (5b) shows them to be quite similar. The WSRT data (figure (5a)) has full polarization, millisecond time resolution, and the data have been dedispersed to remove any pulse smearing across the bandwidth. The similarity of the giant pulse activity in the two records gives us confidence that our Rajkot data are reasonably reliable. Figure (6) shows a record of WSRT data where the giant pulses seem to suddenly get “switched off” within at most a few pulse periods, i.e., within about a second. The expected time scales of such variations from interstellar scintillations (ISS) are many days, more than 5 - 6 orders of magnitude larger than the actually observed time scales. Thus it is unlikely these “switching off” of giant pulses is due to ISS.

It is likely that giant pulses comprise one or more micro-pulses which may be intrinsically extremely bright (Hankins 1971). Popov et al. (2002) and Cairns et al. (2004) found microstructure with characteristic time scales in sub-millisecond range. At least some individual giant pulses observed in B0950+08 with the WSRT at 297 MHz remained unresolved at millisecond time scales (Figure 7), which points to an origin of this giant pulse activity to be an intrinsic phenomenon within the pulsar.

From the data analysis based on a couple of simultaneous observations at 103 MHz at Rajkot and at 297 MHz at Westerbork, there does not appear to be an obvious correlation between the occurrence of individual giant pulses, or even of pulse strength when averaged over minute time scales. It may well be that the giant pulse activity is not very broadband, and indeed the WSRT

PuMa data shows decorrelation of individual pulses within the 10 MHz band. This might agree with a similar conclusion for B1937+21 that the frequency bandwidth of the individual giant radio pulses is relatively narrow (Popov & Stappers 2003). Further observations of these giant pulses with a better sensitivity and time resolution, and preferably at two or more frequency bands simultaneously, are needed to help us in discerning the nature and the ultimate origin of these giant pulses.

The nature of the giant pulses still remains obscure though there are some efforts in this direction (Cairns 2004; Petrova 2004). Equally puzzling is why this phenomenon takes place only in a handful of pulsars. Cognard et al (1996) examined the period P and the period derivative \dot{P} of a few dozen strongest pulsars and estimated the strength of their magnetic field at the light cylinder, $B_{lc} \sim 3 \times 10^8 P^{-2.5} \dot{P}^{0.5}$ G. They noted a rather high value $\sim 10^6$ G for the Crab pulsar ($P = 33$ ms, $\dot{P} = 10^{-12.4}$ sec/sec), as well as PSR B1937+21 ($P = 1.56$ ms, $\dot{P} = 10^{-19}$ sec/sec), which compared to other pulsars is an order of magnitude or more higher. From this they suggested that the giant pulse phenomenon may have something to do with the strength of the magnetic field at the light cylinder radius. Even B1821-24 (Romani & Johnston 2001) has a relatively high $B_{lc} \sim 7 \times 10^5$ G. On the other hand Vela (B0833-45), a giant micropulse emitter, does not have so high a B_{lc} value ($\sim 4 \times 10^4$ G). From the known parameters of PSR 0950+08, ($P = 253$ ms, $\dot{P} = 10^{-15.6}$ sec/sec), we find B_{lc} to be only ~ 150 G, and it does not seem to support the hypothesis that the giant pulse emission physics is particularly dependent on the high magnetic field strength at the light cylinder. It also shows that giant pulses are not all associated with fast pulsars alone.

The extremely high equivalent brightness temperatures of the giant pulses indicate that they originate from nonthermal, coherent emission processes (Hankins et al. 2003). A joint study at radio and γ -rays of the giant pulses from the Crab pulsar (Lundgren et al. 1995) showed that the γ -ray emission remains unchanged during giant radio pulse emission and hence, they concluded that radio coherence is the primary, if not the sole, mechanism for producing fluctuations in the radio emission. They also concluded that the largest giant pulses are a sum of a large ensemble of particularly dense coherently emitting regions and the smaller giant pulses are formed by a smaller number of less dense emission regions. According to this suggestion, it is the fluctuations in the number of charges partaking in the coherent radiation process that gives rise to the intense variation in the net radio emission of the pulse intensity. One can argue that the giant pulse emission and the nulling may be opposite manifestations of the same physical process in a pulsar (Singal 2001), while an enhanced degree of bunching of radiating charges may give rise to a high degree of coherence, resulting in giant pulses, a drop in the degree of coherence may cause nulling.

5. Conclusions

Giant pulses were shown to arise from B0950+08, a normal-period pulsar. The observation made at 103 MHz showed that the energy in these giant pulses exceeded that of the average pulse energy by much more than an order of magnitude. The cumulative intensity distribution of these

giant pulses appears to follow a power law, with power-index -2.2 ± 0.2 , very similar to that seen in other cases of giant pulses detected only in a few fast pulsars, indicating that nature of the giant pulses may be similar in the fast and normal period pulsars.

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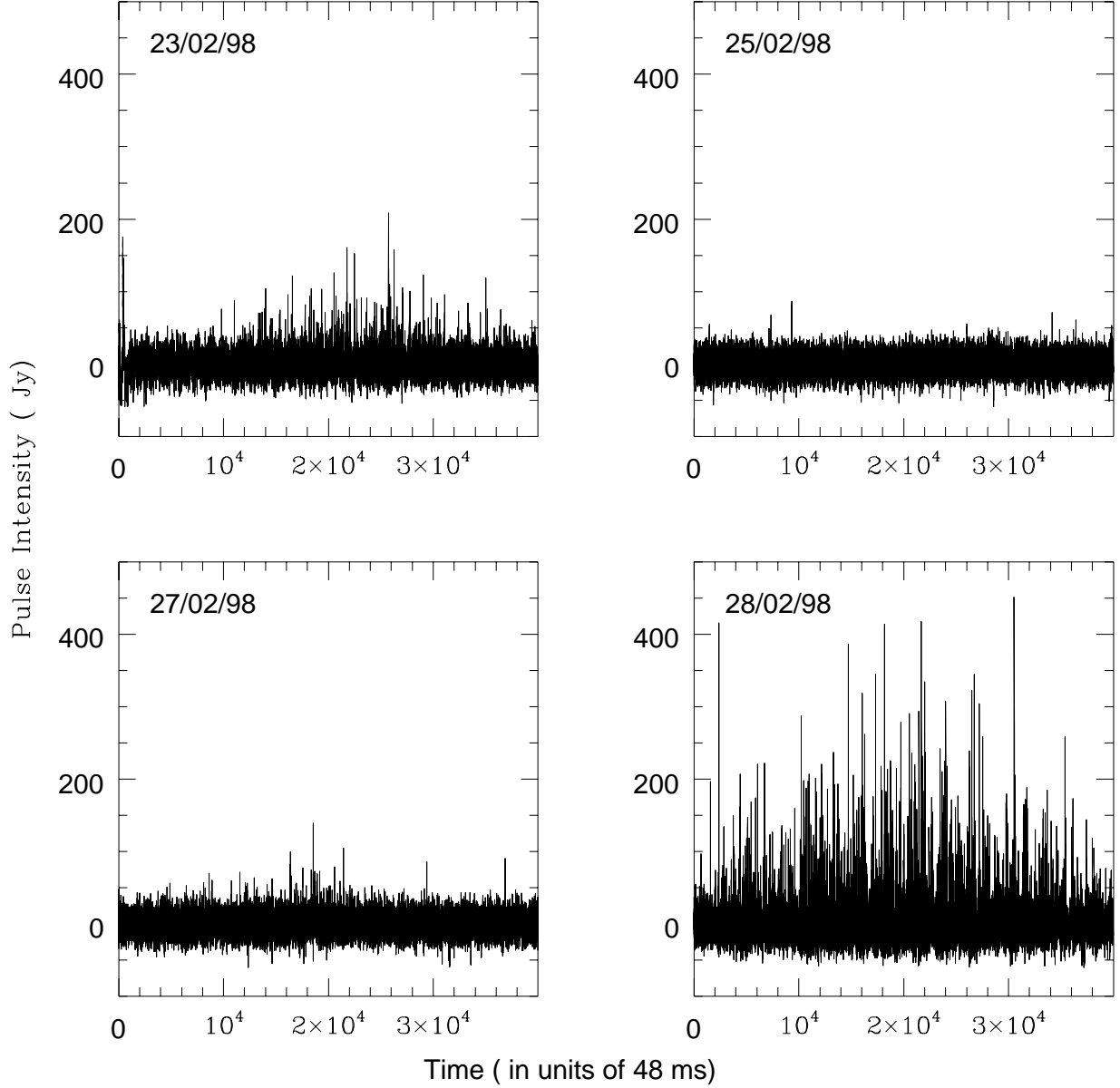


Fig. 1.— A plot of four consecutive observations of PSR B0950+08, showing a total of 40,000 data points in each case. With sampling interval of 48 ms, each observation amounts to an observation time of 32 minutes corresponding to about 7600 pulses. A running average of 1000 data points has been subtracted throughout to remove any slow baseline drifts.

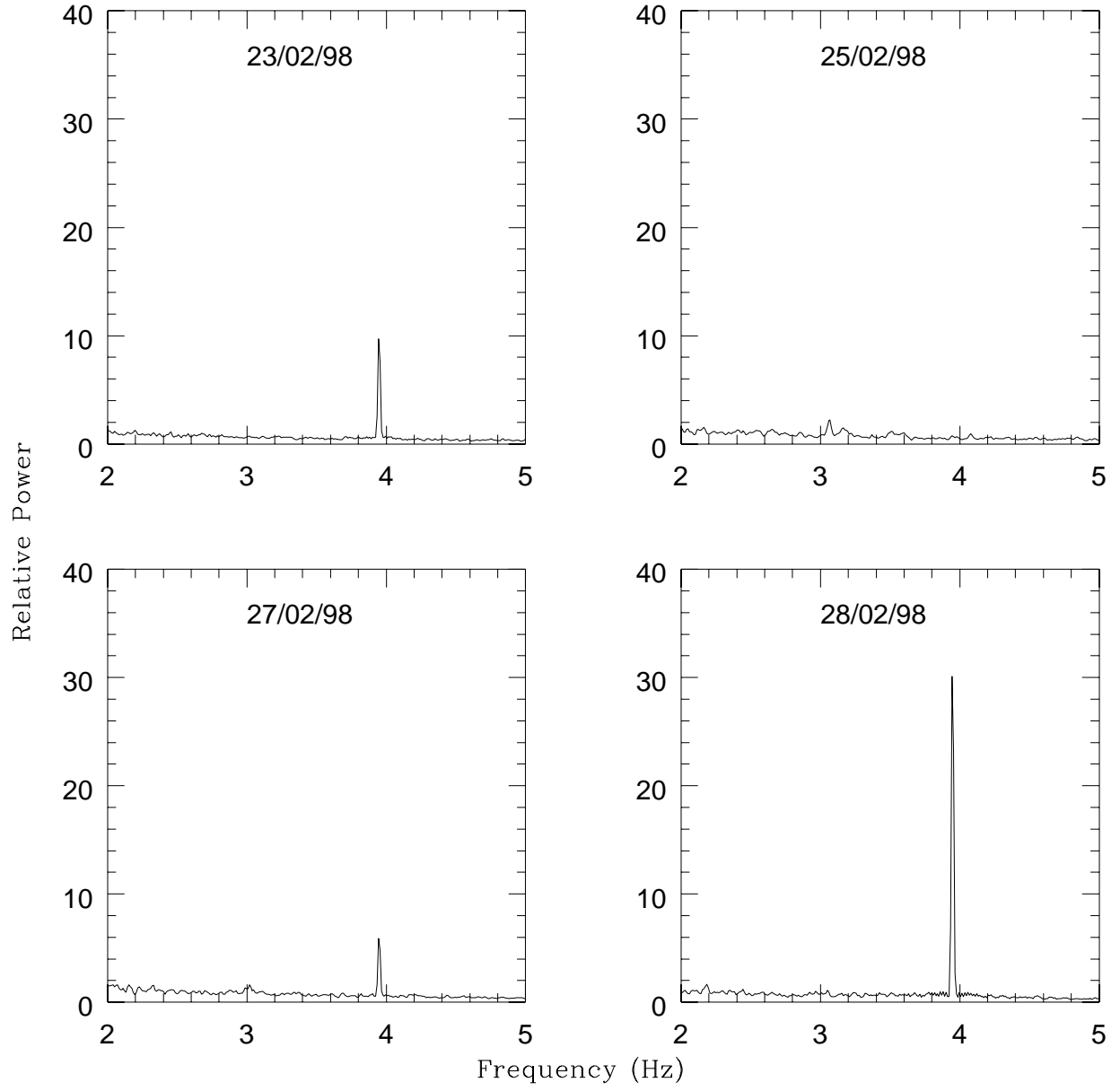


Fig. 2.— Power-spectrum plots of the four observations of figure 1.

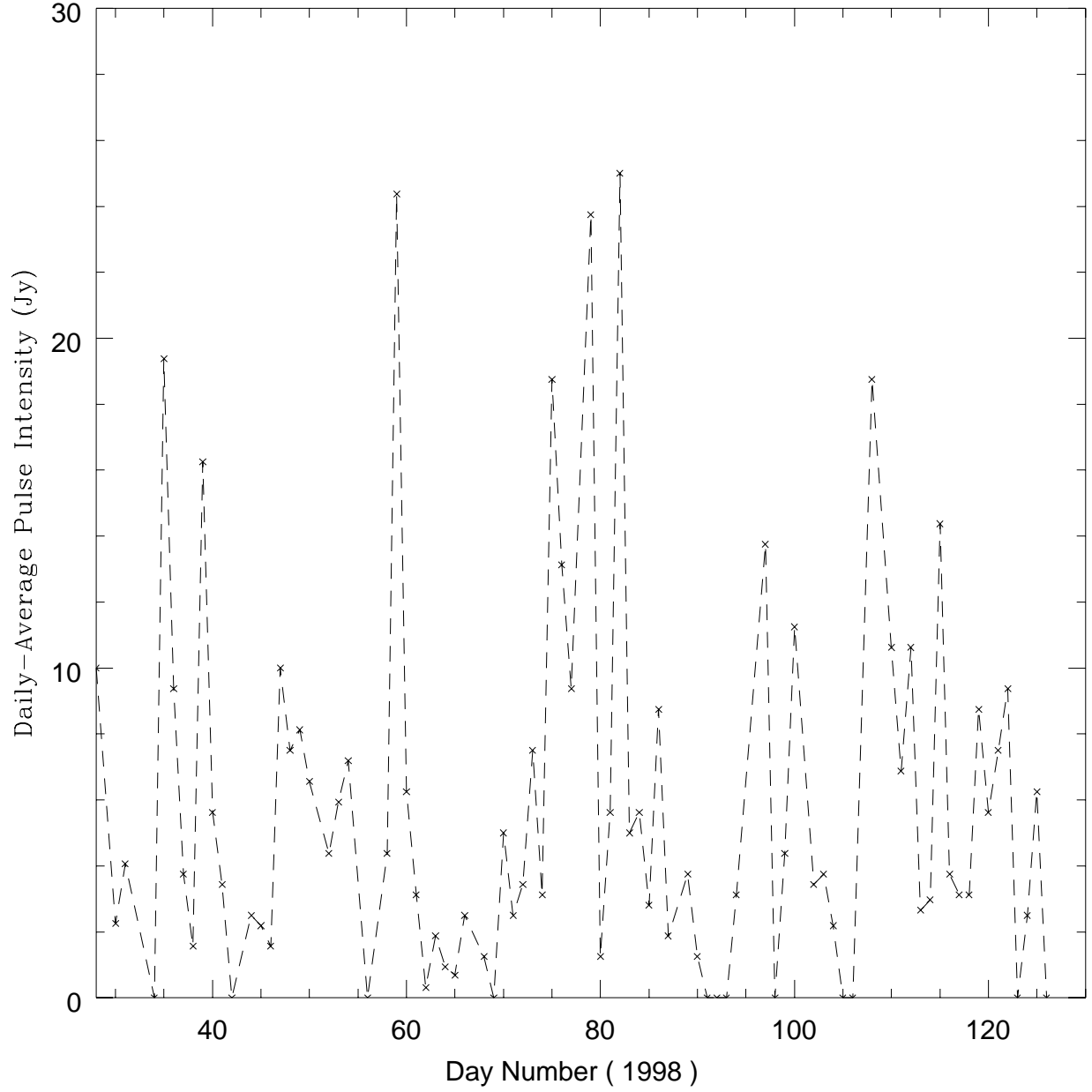


Fig. 3.— A sample plot of the daily average pulse intensities for 84 days of observations in the first half of 1998, obtained mostly between February and April.

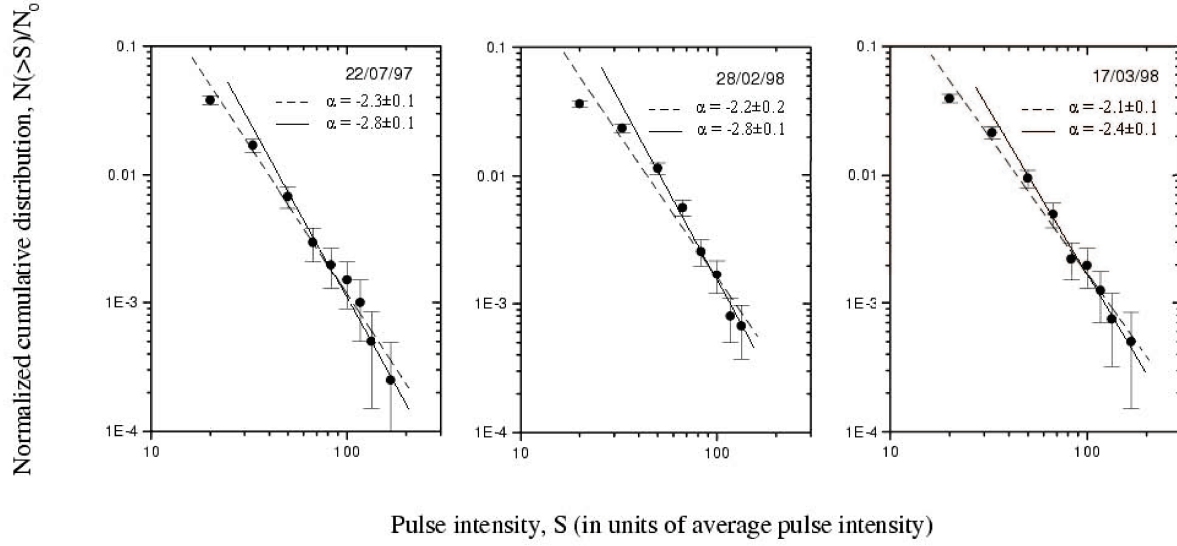


Fig. 4.— Normalized cumulative distribution of the giant pulse intensity shown in log-log plot for three different days of observations. The dashed line in each case shows a power-law fit to the overall observed distribution while the solid line shows a power-law fit to the distribution only at high intensity (> 30 times the average), with the derived slope α steeper in the latter case.

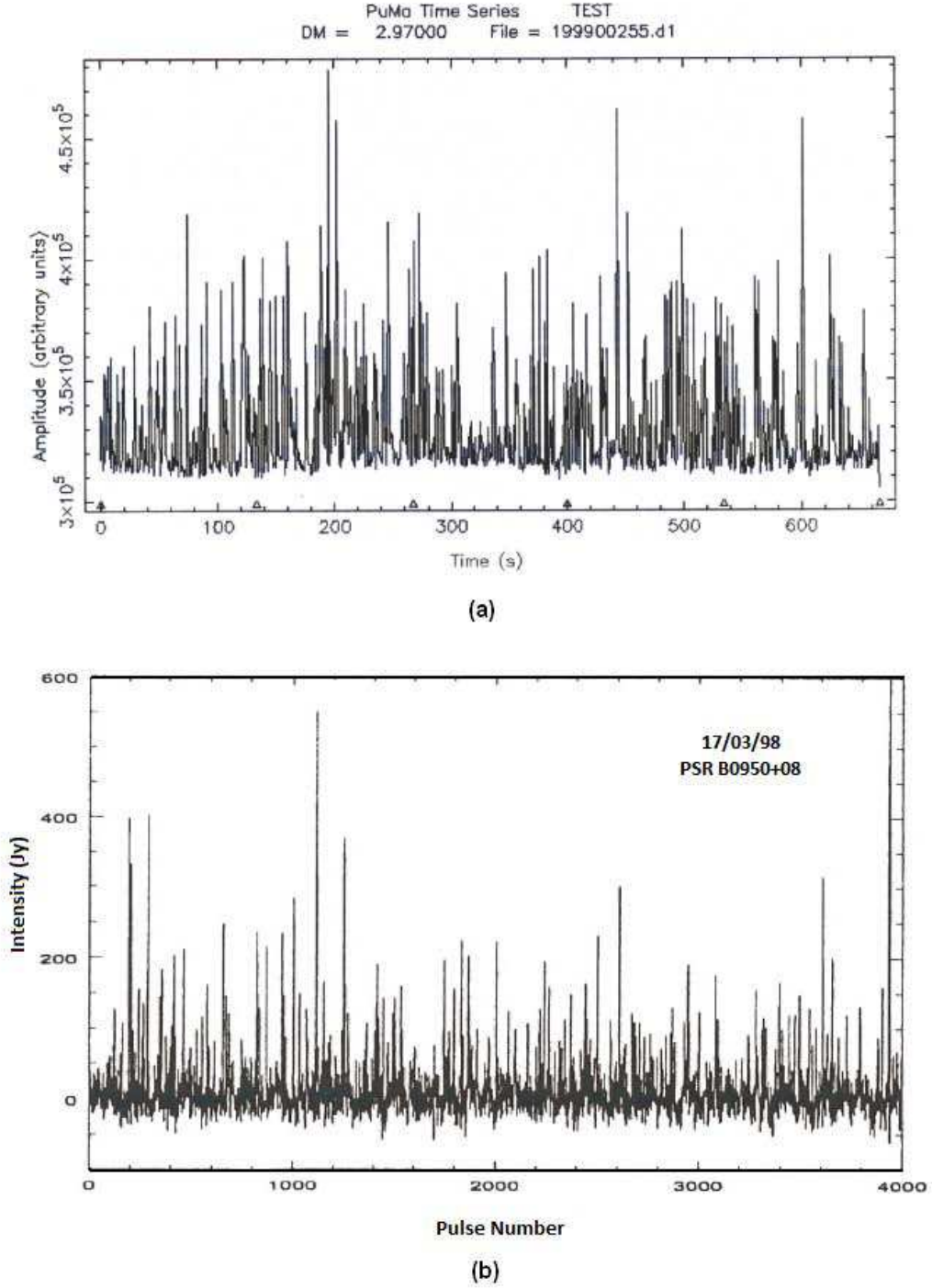


Fig. 5.— (a) A WSRT record of giant pulses at 297 MHz on 12/09/99. (b) Data from the Rajkot Telescope on 17/03/98. The giant pulse distributions in the plots (a) and (b) appear to be quite similar.

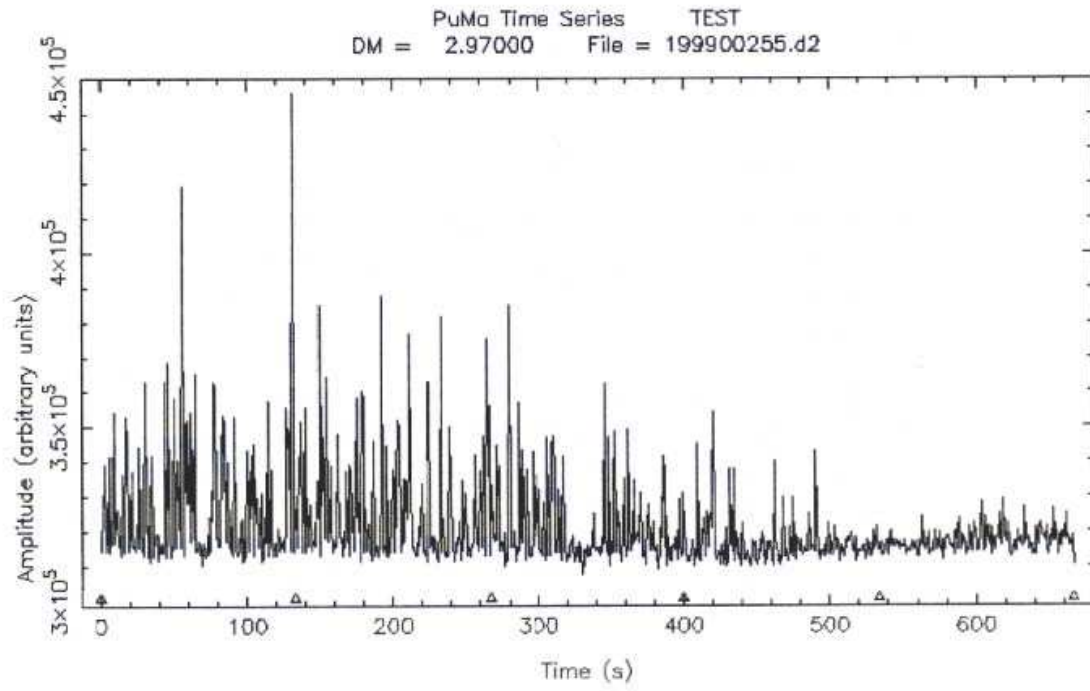


Fig. 6.— A record of WSRT data where the giant pulses suddenly seem to get switched off.

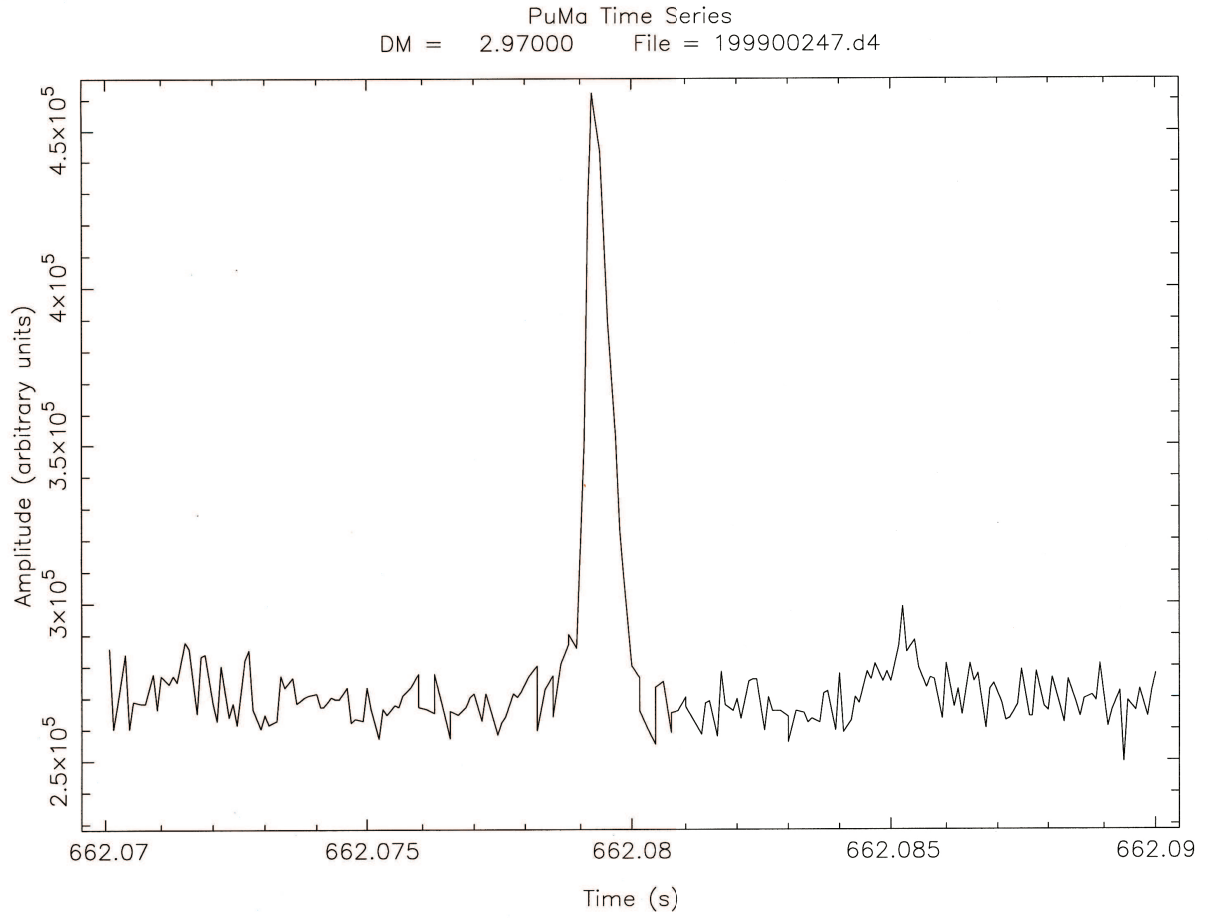


Fig. 7.— A high time resolution of one of the giant pulses observed with the WSRT shows it to be unresolved at millisecond time scales.